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# Geomagnetic field fluctuations during the passage at the Earth's orbit of the tail of the 15–16 July 2000 ejecta

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**Abstract.** In this work we present the analysis of the geomagnetic field fluctuations observed at different ground stations (approximately along two latitudinal arrays, separated by several hours in local time) during the passage at the Earth's orbit of the tail of the 15–16 July 2000 coronal ejecta. The time interval of interest is characterized by northward interplanetary magnetic field conditions and several changes in the solar wind dynamic pressure. We found at all stations, both in the local morning and in the local evening, simultaneous and highly coherent waves at the same discrete frequencies ( $\sim 1.8$  and  $\sim 3.6$  mHz) and suggest a possible interpretation in terms of global compressional modes driven by an impulsive variation of the solar wind pressure. Along the array situated in the morning sector, at the highest latitudes, the higher frequency mode seems to couple with the local field line resonance; on the other hand, along the array situated in the evening sector, the characteristics of the observed fluctuations suggest that the highest latitude station could be located at the footprint of open field lines. Our results also show that solar wind pressure variations observed during the recovery phase of the storm do not find correspondence in the geomagnetic field variations, regardless of local time and latitude; conversely, some hours later continuous solar wind pressure variations find a close correspondence in the geomagnetic field variations at all stations.

**Key words.** Magnetospheric physics (solar wind-magnetosphere interaction; MHD waves and instabilities)

## 1 Introduction

The geomagnetic effects of the passage at the Earth's orbit of solar wind (SW) regions, characterized by variable interplanetary magnetic field (IMF) or plasma parameters, have been studied with great interest in the last few years; in particular, the SW sources of geomagnetic storms, the storm-substorms

relationship and the primary role of the north-south component of the IMF have been well discussed by Kamide et al. (1998) and Gonzalez et al. (1999).

Much attention has also been given to the study of low-frequency fluctuations of the geomagnetic field excited by SW pressure variations (Takahashi, 1998), in particular during quiet geomagnetic conditions, i.e. when the IMF is northward and transient effects such as the onset of a substorm current system and the intensification of the ring current can be neglected. When excited by SW pressure impulsive variations, the magnetosphere behaves as a cavity oscillating at its own eigenfrequencies, which depend on its dimensions and physical characteristics (Radoski, 1974; Kivelson and Southwood, 1985, 1986). Samson et al. (1992) and Walker et al. (1992) extended the cavity model by considering the magnetosphere as an open-ended waveguide in which compressional modes driven by the SW propagate in the antisunward direction. At auroral latitudes, modes at discrete frequencies  $\sim 1.2$ – $1.4$ ,  $1.8$ – $2.0$ ,  $2.4$ – $2.6$  and  $3.2$ – $3.4$  mHz have been observed in several studies and interpreted in terms of local field line resonances excited by the global compressional modes (Samson et al., 1991, 1992; Harrold and Samson, 1992; Walker et al., 1992; Ziesolleck and McDiarmid, 1994, 1995; Mathie et al., 1999). At low latitude, statistical analyses (Ziesolleck and Chaumalaun, 1993; Francia and Villante, 1997; Villante et al., 2001) have shown that modes at these discrete frequencies are characteristic features of the power spectra of the ground magnetic field fluctuations. In addition, studies of individual events reported evidence of oscillations at the cavity/waveguide mode frequencies, which were associated with SW pressure pulses and extended to a major portion of the Earth's magnetosphere, confirming the global character of these fluctuations (Shimazu et al., 1995; Villante et al., 1998; Lepidi et al., 1999). It was observed that, at auroral latitudes, low-frequency pulsations show a clear morning/afternoon asymmetry, with an higher occurrence rate in the morning (Rostoker and Sullivan, 1987; Ziesolleck and McDiarmid, 1995; Chisham and Orr, 1997; Mathie et al., 1999) and that afternoon pulsations are driven dominantly by

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sporadic impulses in the SW (Rostoker and Sullivan, 1987). Consistent with the theory by Mann et al. (1999), who investigated the energization of waveguide modes by magnetosheath flows on the magnetopause flanks, and with the observations by Mathie et al. (1999) and Matthie and Mann (2000), the observed morning/afternoon asymmetry can be explained in terms of a greater stability of the postnoon magnetopause to shear-flow instabilities than the dawn flank; in this sense, pulsations driven by magnetopause instabilities during intervals of enhanced SW speed occur predominantly in the morning, while impulsively driven pulsations may extend over a wide range of local times. It is interesting to note that at low latitude, the occurrence of pulsations at cavity/waveguide mode frequencies is statistically higher in the afternoon (Villante et al., 2001); this feature has been interpreted in terms of SW pressure pulses associated with corotating structures, which more frequently impinge on the postnoon magnetopause.

Impulsive SW pressure increases impacting the Earth's magnetosphere can be considered as a source of global resonant oscillations; on the other hand, it is also possible to observe that more continuous and low amplitude variations of the SW pressure can find a correspondence in the ground magnetic field variations (Ogilvie and Burlaga, 1974; Sibeck et al., 1989). Recently, in a statistical study, Francia et al. (1999) analyzed some events occurring during northward IMF conditions and showed that the geomagnetic field horizontal component  $H$  at a low-latitude station (L'Aquila) responds very well to the SW pressure variations on a time scale of few minutes. The amplitude of the geomagnetic response was found to be linearly related to the change in the square root of the SW dynamic pressure, and its average amplitude ( $\sim 13 \text{ nT}/(\text{nPa})^{1/2}$ ) is comparable with the values found by Russell et al. (1994) and Russell and Ginskey (1995) at low and subauroral latitudes in the analysis of the sudden impulse (SI) response to the passage of interplanetary shocks. Moreover, the amplitude of the response was found to depend on local time, with greater values around local noon and midnight and a pronounced minimum during the local morning. A similar local time dependence, although characterized by a greater excursion between maximum and minimum values, was also found by Russell and Ginskey (1995) in the analysis of SIs at subauroral latitudes (near  $55^\circ$ ).

The great variety of recent studies on these subjects indicates that the occurrence and the global character of the geomagnetic response to both impulsive and continuous stimulations from the SW, as well as the local time and latitudinal dependence of the properties of the observed phenomena, are outstanding problems. In this context, we present a case study of the ground response to SW pressure variations occurring during a long duration period of northward IMF in the recovery phase of the major geomagnetic storm of 15–16 July 2000; in particular, we analyzed the geomagnetic field fluctuations observed at several ground stations along two arrays spanning from low to auroral latitudes and separated by several hours in magnetic local time. We found a very strong

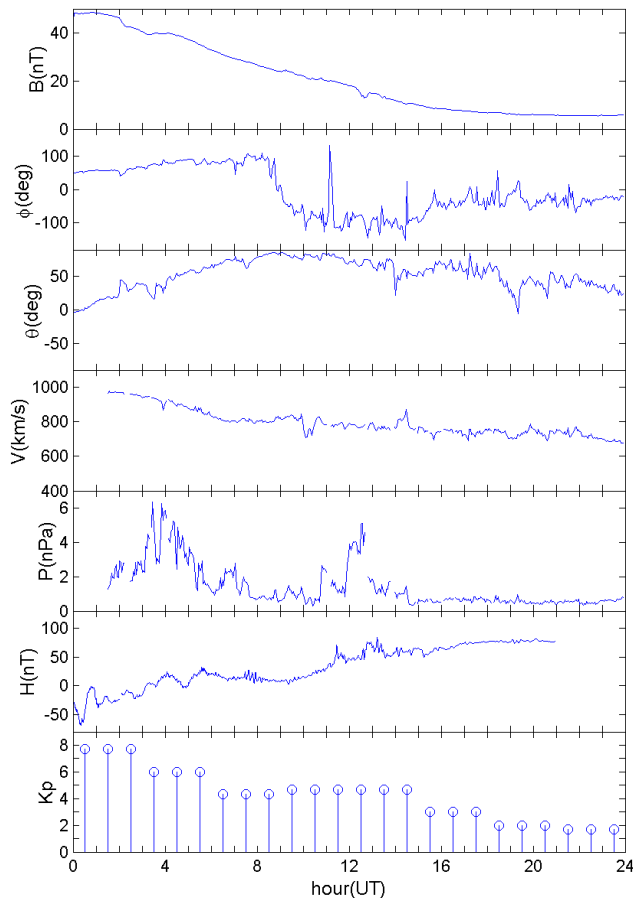
**Table 1.** IGRF 2000 corrected geomagnetic latitude, MLT midnight in UT and  $L$  value for the stations

Station	CGM lat ( $^\circ$ N)	MLTMN (UT)	$L$
SOD, Finland	63.9	21:03	5.24
NUR, Finland	56.9	21:24	3.40
BFE, Denmark	52.0	22:17	2.69
NGK, Germany	48.0	22:17	2.27
BDV, Czech Republic	44.5	22:16	1.99
CTS, Italy	41.0	22:27	1.77
AQU, Italy	36.3	22:23	1.56
CHD, Russia	65.0	15:09	5.67
ZYK, Russia	59.9	14:49	4.03
MGD, Russia	53.8	14:41	2.90
PTK, Russia	46.4	14:09	2.10
MSR, Japan	37.6	14:59	1.60
ONW, Japan	31.5	15:00	1.40

similarity of the geomagnetic field variations at all the stations, independent of latitude and magnetic local time, which indicates the global character of the response of the magnetosphere, when excited by variations of the SW pressure. Our results also show that the geomagnetic response to the external stimulations is not always clearly detectable, depending on magnetospheric conditions; in particular, an impulsive variation of the SW pressure, occurring when the IMF northward conditions persist for several hours, triggers along both arrays simultaneous and highly coherent pulsations at the same discrete frequencies, which can be interpreted in terms of global compressional modes; also, continuous SW pressure variations occurring some hours later find a close correspondence in geomagnetic field variations, regardless of local time and latitude; conversely, we do not observe any clear common geomagnetic response to the larger SW pressure variations occurring some hours earlier, during the recovery phase of the storm.

## 2 Experimental results

We used 1-min values of the geomagnetic field horizontal component  $H$  measured along two meridional arrays separated by approximately 6–8 hours in magnetic local time (Table 1). The first array consists of seven geomagnetic stations in Europe spanning over the latitude range between  $\sim 36^\circ$  N and  $\sim 64^\circ$  N at approximately (within  $\sim 1.5$  h) the same magnetic local time: the Italian stations of L'Aquila (AQU) and Castello Tesino (CTS) and five INTERMAGNET stations. The second array consists of six stations along the 210 MM (within 1 hour) and spans almost the same latitudinal interval between  $31.5^\circ$  N and  $65^\circ$  N. For the SW and IMF measure-

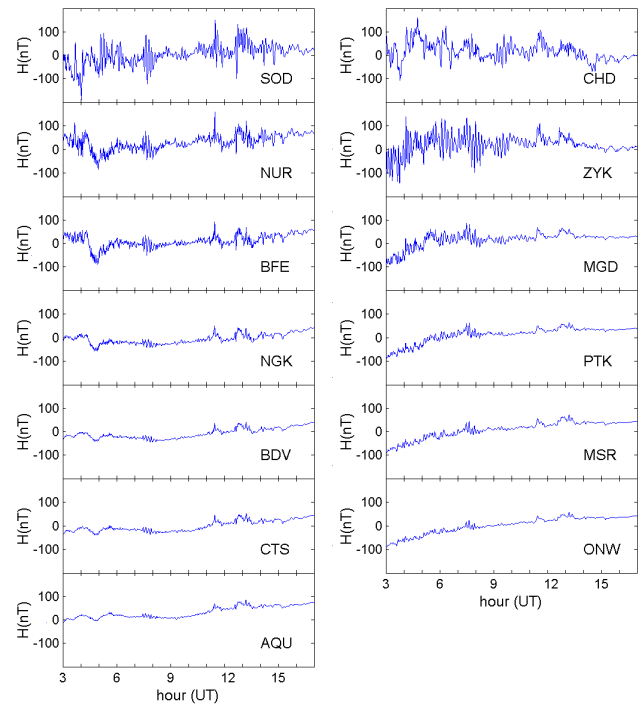


**Fig. 1.** ACE measurements, ground observations from AQU and  $K_p$  index on 16 July 2000. From top to bottom are shown the IMF strength and its longitude and latitude in the ecliptic angular coordinates, the SW flow speed and dynamic pressure, the variations of the horizontal geomagnetic field component  $H$  at AQU and the  $K_p$  index.

ments, we used the 64-s and 16-s averages, respectively, from the ACE spacecraft at the L1 point ( $\sim 247 R_E$  in the radial direction).

The 15–16 July 2000 ejecta arrived at the ACE position at about 19:00 UT on 15 July 2000 and was characterized by an unusually strong (with values up to  $\sim 60$  nT) southward directed IMF and by an extremely high SW velocity. The high rate of particles caused spacecraft anomalies, and reliable SW data are available only from 16 July, when the ejecta still engulfed the Earth.

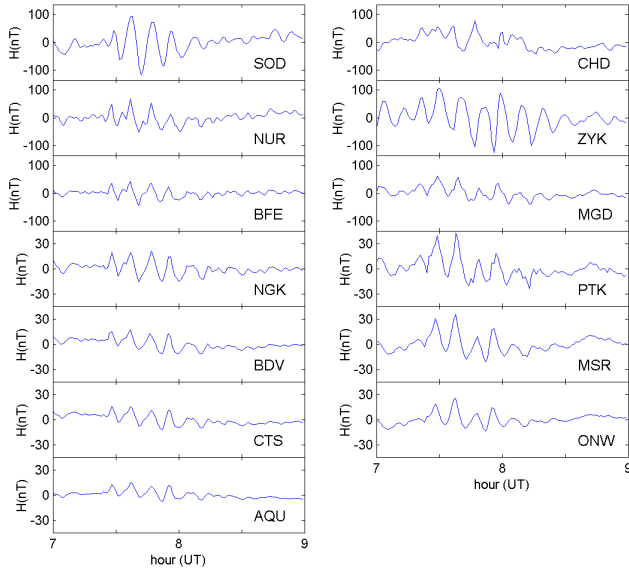
In Fig. 1, we show the  $H$  component of the geomagnetic field at AQU, the  $K_p$  index values and the simultaneous IMF and plasma data (smoothed by means of 3-min running averages with a step size of 1 min) on 16 July 2000. As can be seen, the IMF strength decreased progressively throughout the day and its direction turned northward ( $\theta > 0$ ) from  $\sim 01:00$  UT (in the preceding hours, the strong southward component caused an intense geomagnetic storm with the  $D_{st}$  index reaching 300 nT). The SW data show several gaps; however, we can see that the velocity was still



**Fig. 2.** Variations of the horizontal geomagnetic field  $H$  component at the different stations from 03:00 UT to 17:00 UT on 16 July 2000. Left and right panels correspond to the European and the Asiatic array, respectively.

very high, with values slowly decreasing from  $\sim 1000$  km/s to  $\sim 700$  km/s, while the dynamic pressure was characterized by several large amplitude variations until  $\sim 15:00$  UT. On the ground at AQU, during the local morning, the magnetic field was still disturbed due to the previous southward IMF conditions (a clear signature of a bay before 01:00 UT can be noted), but it was slowly recovering to its prestorm values; as for the  $K_p$  index, its value changed from  $8^-$  at the beginning of the day to  $4^+$  in the time interval 06:00–09:00 UT, to  $5^-$  between 09:00 and 15:00 UT and then decreased to 3 and  $2^-$  in the following hours. We can observe that the  $H$  component shows wave activity from the very early morning, in correspondence with the large variations of the SW pressure observed by ACE from  $\sim 03:00$  UT. At  $\sim 07:20$  UT, the waves became more regular and quasi-monochromatic oscillations are observed for several cycles until  $\sim 08:10$  UT; minor amplitude pulsations are also detected from 09:00 UT. A very evident feature emerging from Fig. 1 is that, between  $\sim 11:00$ – $15:30$  UT, the oscillations appear superimposed on longer period variations and the whole pattern, although time-delayed, closely resembles the large SW pressure variations observed by ACE between  $\sim 10:30$ – $15:00$  UT. Conversely, it can be noted that, during the local morning, the  $H$  component pattern does not show any resemblance to the strong SW pressure changes observed in the time interval 03:00–07:40 UT.

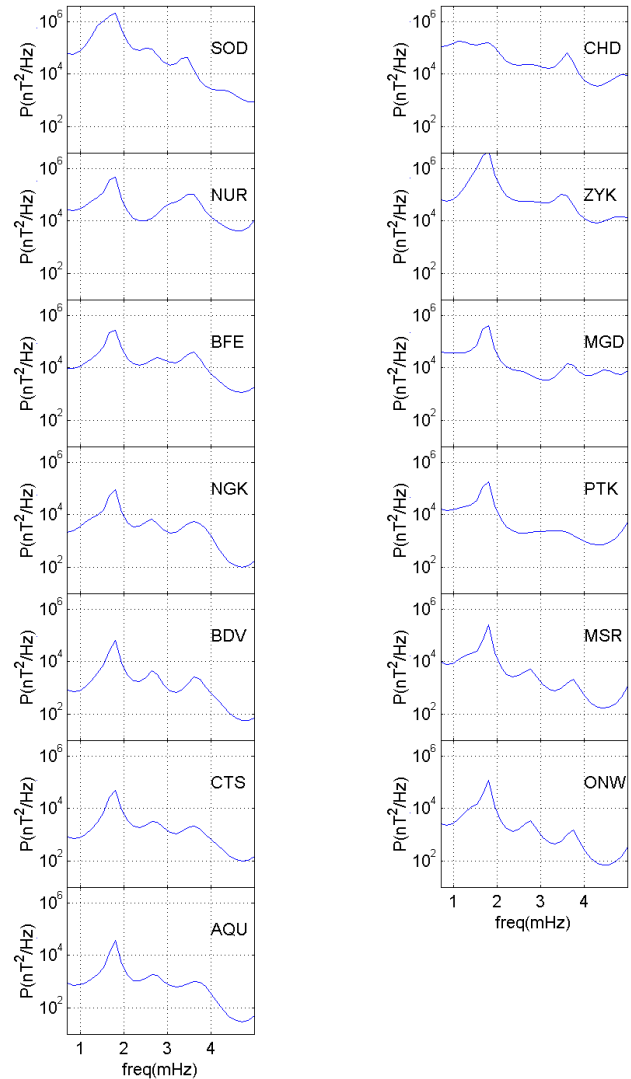
In order to investigate the spatial extent of the observed geomagnetic field variations, we also examined the geomag-



**Fig. 3.** Oscillations of the horizontal geomagnetic field  $H$  component in the time interval 07:00–09:00 UT at the different stations.

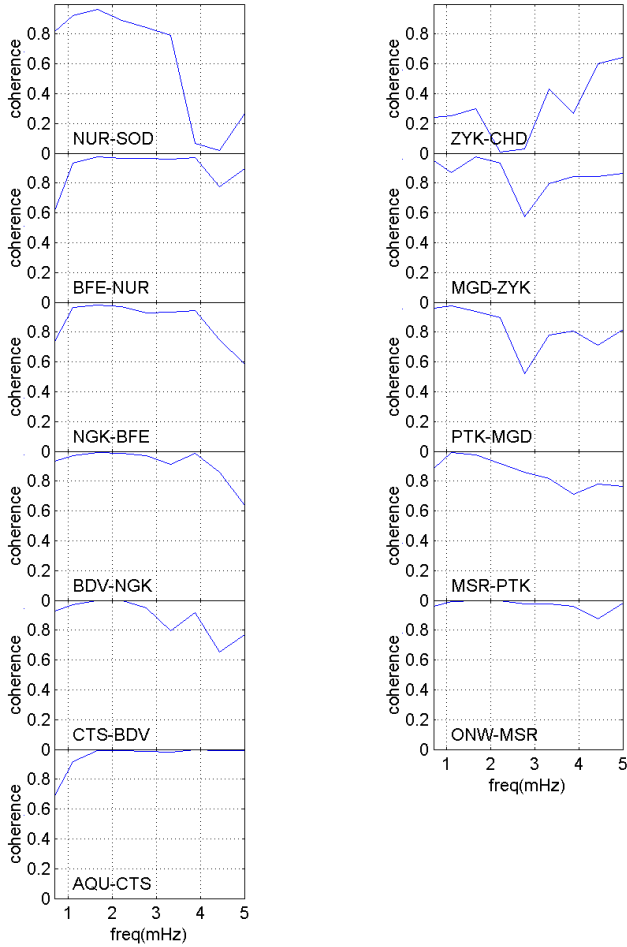
netic data at the other ground stations in the time interval 03:00–17:00 UT (Fig. 2). The quasi-monochromatic fluctuations observed at AQU during the 07:20–08:10 UT time interval are clearly detected both along the European and the 210 MM array (except perhaps at the highest station CHD), located in the local morning and in the local afternoon, respectively, and their amplitude increases with increasing latitude, as can be expected for fluctuations having a common external source. Also, the pattern of the continuous variations observed at AQU between 11:00–15:30 UT (i.e. in the afternoon and in the pre-midnight sector along the European and the 210 MM array, respectively) is evident at the different stations, although at the highest latitudes, it is partially masked by strong, higher frequency fluctuations. Note that the SW pressure variations observed between 03:00–07:40 UT do not find any clear correspondence in the  $H$  variations, nor at the European or the 210 MM stations (in the morning and postnoon sector, respectively), except at the highest station CHD, where the  $H$  variations seem to follow, with some delay, the SW pressure changes.

In Fig. 3, we plot the regular oscillations on the  $H$  component in the time interval 07:00–09:00 UT at the different stations. It can be noted that the onset of the pulsations, at  $\sim 07:20$  UT, is abrupt and simultaneous at all stations; as previously noted, at CHD, the pulsations are less evident and are masked by the pattern of the  $H$  variations corresponding to the SW pressure variations observed from ACE between  $\sim 06:40$ – $07:40$  UT. A spectral analysis of the oscillations in the 07:00–09:00 UT time interval was performed using the maximum entropy method of the order of  $m = 20$  of the prediction error filter (with a frequency resolution of about 0.14 mHz). We found that at all stations the power spectra show peaks at discrete frequencies, namely at 1.8 and 3.6 mHz (Fig. 4); some evidence for a third peak, less



**Fig. 4.** Power spectra of the horizontal geomagnetic field  $H$  component in the time interval 07:00–09:00 UT at the different stations.

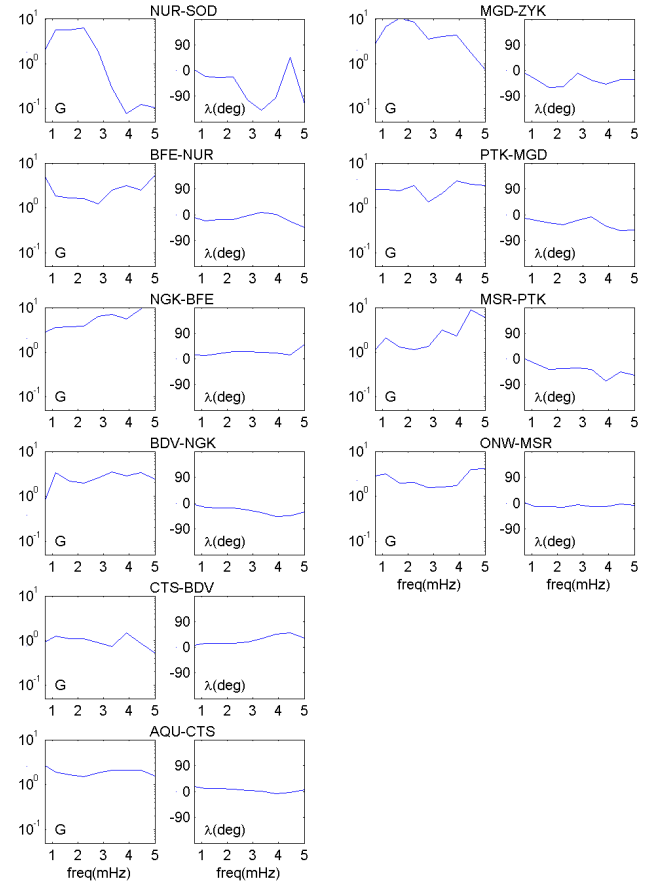
clear than the previous ones, also emerges at 2.6 mHz. These frequencies are close to those detected at auroral latitudes (Mathie et al., 1999 and references therein) which are generally interpreted in terms of field line resonances set up by the compressional magnetospheric waveguide modes. Along the European array, the power of the 1.8 mHz peak monotonically increases with increasing latitude from AQU to SOD; the 3.6 mHz peak shows a similar behaviour only up to the latitude of NUR, where its power is maximum; then at SOD it has a lower power content and appears shifted to a slightly lower frequency (3.5 mHz). Along the 210 MM array, the power of both the 1.8 mHz and the 3.6 mHz peaks increases with latitude up to ZYK (although at PTK, the 3.6 mHz peak is broader and shifted to a lower frequency) and then decreases at the latitude of CHD, where the 1.8 mHz peak is also partially masked by the higher power content at lower frequencies. For the two-hour interval 07:00–09:00 UT, we



**Fig. 5.** Coherence between the horizontal geomagnetic field  $H$  component in the time interval 07:00–09:00 UT at pairs of adjacent stations.

also computed the coherence of the  $H$  component between couples of adjacent stations (with  $8^\circ$  of freedom, i.e. averaging four 30-min intervals). It can be seen from Fig. 5 that in Europe, for fluctuations up to 4 mHz, the coherence is very high ( $>0.8$ ) from AQU to NUR, while between NUR and SOD it shows an abrupt decrease at frequencies higher than 3.3 mHz; in Asia, the coherence is high up to ZYK, although at latitudes between PTK and ZYK, it shows a pronounced minimum around  $\sim 2.7$  mHz (note from the corresponding spectra in Fig. 4 that the power peak at this frequency disappears), while between ZYK and CHD it is low in the whole frequency range.

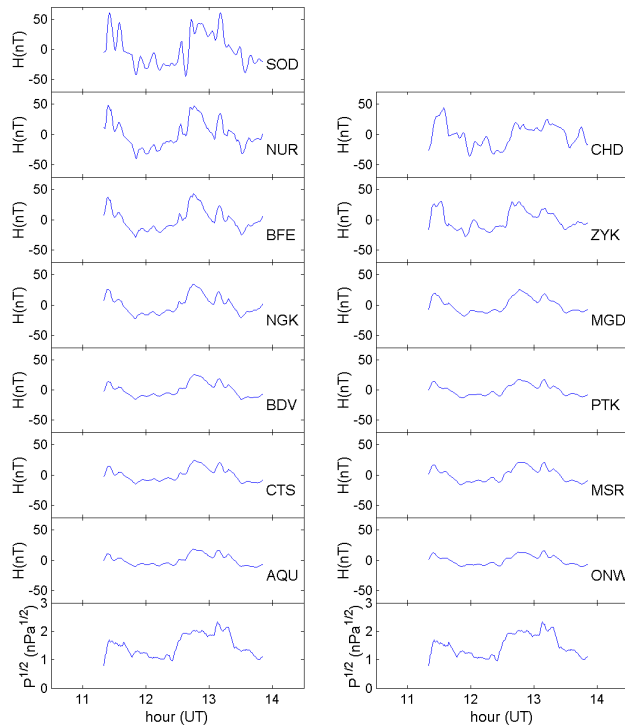
From the previous results, it is evident that along the 210MM array, the 1.8 mHz and the 3.6 mHz modes show similar characteristics: their power increases with increasing latitude and their coherence remains high up to the latitude of ZYK ( $\sim 60^\circ$ ); at CHD ( $65^\circ$ ), although the two power peaks are still present, their power is lower and the corresponding fluctuations are decoupled from those detected at the other stations. On the other hand, in Europe, the two modes show different characteristics: the 1.8 mHz fluctuations are highly



**Fig. 6.** Spectral ratio  $G$  and phase difference  $\lambda$  between the horizontal geomagnetic field  $H$  component in the time interval 07:00–09:00 UT at pairs of adjacent stations (assuming the lower latitude station as the input).

coherent over the whole latitudinal range ( $\sim 36^\circ$ – $64^\circ$ ) and their power increases monotonically with increasing latitude; conversely, the higher frequency (3.6 mHz) fluctuations are coherent up to NUR ( $\sim 57^\circ$ ), where their power maximizes; then, between NUR and SOD ( $\sim 64^\circ$ ), the coherence strongly decreases and at SOD, the frequency is slightly lower and the power decreases. These features might be signatures of a field line resonance at  $\sim 3.6$  mHz between NUR and SOD (Southwood, 1974; Chen and Hasegawa, 1974; Waters et al., 1995), which takes energy from the coupling with the magnetospheric compressional mode. The evaluation of the spectral ratio  $G$  (or gain factor) and the phase difference between the  $H$  components at two adjacent stations can be used as an additional method to investigate this possibility (Baransky et al., 1985; Waters et al., 1991; Menk et al., 2000). In general, this method requires that the spatial separation between the stations should be small enough to maintain adequate coherence in the wave fields (Waters et al., 1995), but also large enough to resolve the variation of the phase difference; in our study, the separations between pairs of adjacent stations (from  $3^\circ$  to  $8^\circ$ , and in particular,  $7^\circ$  for the couple NUR–SOD) are larger than in the study by Waters et al. (1995);





**Fig. 7.** The square root of the SW pressure and the  $H$  component at the different stations in the time interval 11:20–13:51 UT (SW data are shifted for the time delay of 37 min).

however, Menk et al. (1999), using station pairs spaced up to  $\sim 6^\circ$ , have shown that, for some events, resonance signatures can also be obtained for the most widely spaced station pairs. In Fig. 6, we show the spectral ratio and the phase difference for couples of adjacent stations, assuming the lower latitude station as the input; we do not show the two parameters for the stations ZYK-CHD, among which the signals are decoupled. We can note that for latitudes up to NUR in Europe and ZYK in Asia, both the gain and the phase difference do not exhibit any significant frequency dependence; moreover, the spectral ratio  $G$  is greater than 1, indicating the latitudinal increase in the amplitude of the fluctuations. Conversely, between NUR and SOD, both parameters show around 3 mHz, in correspondence to the sharp decrease in the coherence (Fig. 5), the predicted behavior for resonant phenomena: the spectral ratio decreases smoothly from  $G > 1$  to  $G < 1$  and the phase difference reaches minimum values. Thus, along the European array, the 3.5–3.6 mHz compressional mode seems to couple with the local field line resonance between NUR and SOD, while along the Asiatic array the pulsations characteristics seem to indicate a dominantly compressional mode up to ZYK.

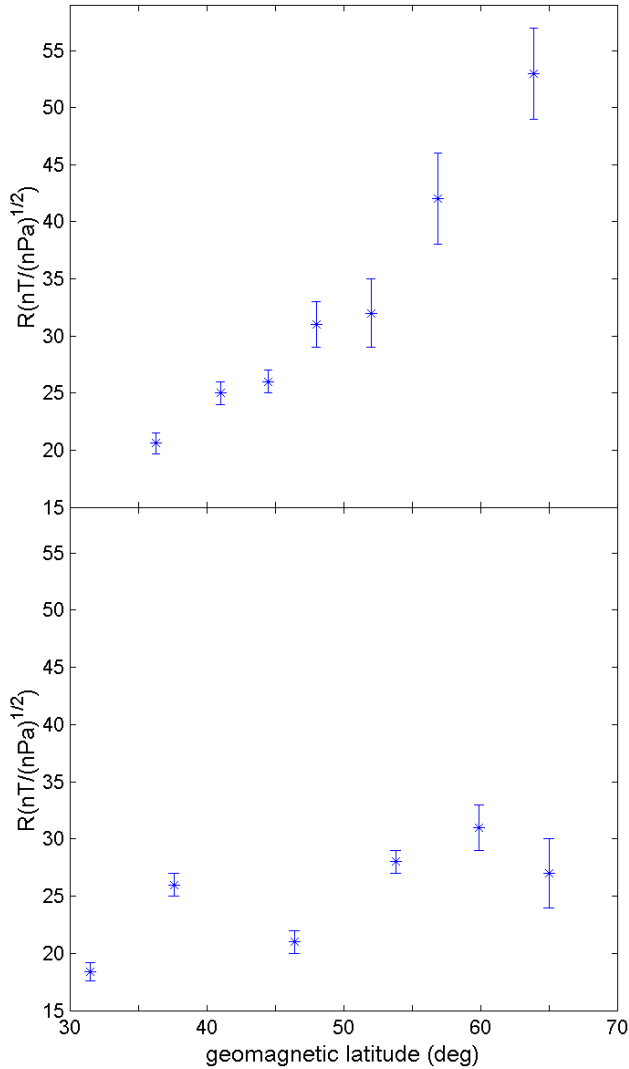
We also analyzed the close correspondence between the geomagnetic field  $H$  component and the SW pressure variations observed at all stations around 12:00 UT, i.e. just after the local magnetic noon and in the local evening along the European and the 210 MM arrays, respectively. In order to quantitatively investigate this aspect, we estimated, for

**Table 2.** The parameters of the linear fit between the  $H$  component at the different stations and the square root of the SW dynamic pressure

Station	$\rho$	$R(\text{nt}/(\text{nPa})^{1/2})$
SOD, Finland	0.71	$53 \pm 4$
NUR, Finland	0.71	$42 \pm 4$
BFE, Denmark	0.69	$32 \pm 3$
NGK, Germany	0.77	$31 \pm 2$
BDV, Czechoslovakia	0.84	$26 \pm 1$
CTS, Italy	0.85	$25 \pm 1$
AQU, Italy	0.87	$21 \pm 1$
CHD, Russia	0.55	$27 \pm 3$
ZYK, Russia	0.75	$31 \pm 2$
MGD, Russia	0.85	$28 \pm 1$
PTK, Russia	0.87	$21 \pm 1$
MSR, Japan	0.87	$26 \pm 1$
ONW, Japan	0.88	$18 \pm 1$

different time delays, the correlation coefficient  $\rho$  between the  $H$  component at each station in the time interval 11:20–13:51 UT and the square root of the SW pressure. We used 6-min running averages (with a step size of 1-min) of both the SW and geomagnetic data to rule out the shortest period variations and then detrended the geomagnetic data to eliminate the long-term variations. At all stations, we found the highest values of  $\rho$  coefficients for a time delay of 37 min, which is comparable to the SW estimated transit time along the radial direction between ACE and the subsolar point of the bowshock ( $\sim 31$  min, at an average speed of  $\sim 800$  km/s) plus a few minutes due to the propagation to the ground (similar results on the time delay between spacecraft and ground observations were also found in the analysis by Francia et al., 1999); in Fig. 7, we show the square root of the SW pressure (the data have been shifted for the time delay of 37 min) and the  $H$  component at the different stations in the time interval of interest. The similarity of the variations detected at all the stations, as well as their close correspondence with the SW pressure variations, are really striking.

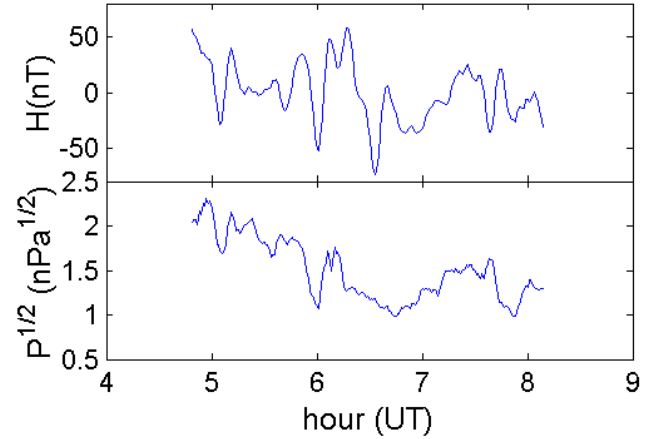
Table 2 gives the values of the correlation coefficient at each station and the corresponding geomagnetic response  $R$  computed as the slope of the least-squares linear approximation between  $H$  and the square root of the SW pressure values. It can be noted that the correlation is high for all stations, except for the highest latitude station along the 210 MM array. As made clear in Fig. 8, along the European array, the amplitude of the response increases monotonically with the geomagnetic latitude of the station and the growth seems more steep beyond  $\sim 55^\circ$  ( $L \sim 3$ ). In particular, it can be seen that the value of the response at AQU ( $21 \text{ nT}/(\text{nPa})^{1/2}$ ) is slightly higher than the value found previously just after the local noon ( $17.5 \text{ nT}/(\text{nPa})^{1/2}$ ) in the statistical analysis of



**Fig. 8.** The ground response  $R$  versus the geomagnetic latitude of the stations for the European array (upper panel) and the Asiatic array (lower panel).

Francia et al. (1999) and that at the subauroral station NUR, it is higher ( $42 \text{ nT}/(\text{nPa})^{1/2}$ ) than the geomagnetic response level (between  $20\text{--}30 \text{ nT}/(\text{nPa})^{1/2}$ ) observed after local noon by Russell and Ginskey (1995) in the statistical analysis of SIs at subauroral latitudes. Figure 8 also shows that, along the 210 MM array, situated in premidnight sector, the latitudinal dependence of the response is not clearly defined: in particular, some evidence for a latitudinal increase in the response (although less steep than along the European array) emerges up to ZYK; however, an anomalous high response is observed at MSR, with a value ( $26 \text{ nT}/(\text{nPa})^{1/2}$ ) much higher than observed previously at approximately the same latitude during the local evening ( $\sim 14 \text{ nT}/(\text{nPa})^{1/2}$ ) in the statistical study of Francia et al. (1999). Also, the response at MGD is much higher with respect to the value found for the same local time by Russell and Ginskey (1995) at subauroral latitudes.

We noted previously the lack of a geomagnetic response



**Fig. 9.** The square root of the SW pressure and the  $H$  component at CHD in the time interval 04:50–08:10 UT (SW data are shifted for the time delay of 37 min).

to the continuous SW pressure variations observed between 03:00–07:40 UT, not only along the European array in the local morning (when the amplitude of the response at mid-latitudes should be minimum, Francia et al., 1999), but also at the 210 MM stations after the local noon (when its amplitude at mid-latitudes should be high, Francia et al., 1999); this feature seems to indicate that the magnetosphere, which is still recovering from a major geomagnetic storm, does not clearly respond to the continuous SW pressure variations. We noted, however, that some correspondence with the SW pressure variations emerges at CHD from  $\sim 05:00$  UT (Fig. 9); for this station we computed the correlation coefficient between the  $H$  component variations in the time interval 04:50–08:10 UT and the SW pressure variations and found that the highest value ( $\rho = 0.54$ ) is also obtained, in this case, for a delay time of 37 min, and that the amplitude of the response,  $41 \pm 5 \text{ nT}/(\text{nPa})^{1/2}$ , is higher than the value obtained at the same station in the premidnight sector. The estimate of a delay time of 37 min between the SW pressure and the CHD geomagnetic variations in the time interval 04:50–08:10 UT, also suggests that the quasi-monochromatic fluctuations observed at all stations from  $\sim 07:20$  UT could be triggered by the sudden change in the SW pressure at  $\sim 06:40$  UT. On this point, we note that from a spectral analysis of the SW pressure (not shown), no evidence emerges for waves at the same discrete frequencies observed on the ground, so the geomagnetic oscillations are not directly driven by periodic pressure variations.

### 3 Summary and discussion

This paper is focused on the study of the geomagnetic effects related to the impact on the magnetopause of SW regions characterized by several pressure variations during northward IMF conditions. In particular, we analyzed the geomagnetic field variations observed on 16 July 2000, in correspondence to the passage at the Earth's orbit of the tail of the 15–16 July coronal ejecta; during the analyzed time in-



terval, the magnetosphere was recovering from a major geomagnetic storm (with the  $D_{st}$  index reaching 300 nT). For this study, we used geomagnetic field data from several stations located approximately along two latitudinal arrays, in Europe and in Asia, both spanning from low to auroral latitudes and separated by approximately 6–8 h in magnetic local time.

A very strong similarity of the geomagnetic field variations at all the stations, independent of latitude and magnetic local time, emerges, suggesting that the magnetosphere, when excited by variations of the SW pressure, exhibits a global response. In particular, we find that highly coherent fluctuations at the same discrete frequencies (1.8 and 3.6 mHz) are observed simultaneously at the different stations along the two arrays (situated in the local morning and in the local afternoon), in correspondence to an impulsive variation of the SW pressure; the frequencies of the observed fluctuations correspond, within the statistical uncertainty ( $\sim 0.14$  mHz), to the frequencies of the magnetospheric cavity/waveguide modes (Samson et al., 1991, 1992; Harrold and Samson, 1992; Walker et al., 1992; Ziesolleck and McDiarmid, 1994, 1995; Mathie et al., 1999). We note that the SW speed in the period of interest is very high ( $\sim 800$  km/s), so we could expect the magnetopause to be unstable to shear-flow instabilities on both flanks and to amplify the waveguide modes set up by the SW pressure variation (Mann et al., 1999; Mathie and Mann, 2000).

Along the European array, situated in the local morning, the 1.8 mHz mode is highly coherent, without any significant phase difference, and its power increases with increasing latitude through the whole latitudinal extension, as can be expected for a dominantly compressional mode. As for the 3.6 mHz mode, we find it interesting to observe that its characteristics appear to change from the latitude of NUR ( $\sim 57^\circ$ ), where its amplitude is maximum; indeed, the coherence between different couples of adjacent stations, very high at lower latitudes, between NUR and SOD, strongly decreases. The results of a cross-spectral analysis conducted between the stations of NUR and SOD, with the evaluation of the spectral ratio and phase difference, indicate at about 3 mHz the characteristic behaviour of local field line resonant phenomena (Waters et al., 1991; Menk et al., 2000). In this sense, we suggest a coupling between the global magnetospheric compressional mode at 3.6 mHz and the local field line resonance at latitudes of the order of  $60^\circ$ .

Along the Asiatic array, located in the local afternoon, up to the latitude of ZYK ( $60^\circ$ ), the power of both modes increases with increasing latitude, and the fluctuations are highly coherent and do not show any significant phase difference, indicating that the compressional modes do not couple with local field line resonances. We also found that at the highest latitude station CHD ( $65^\circ$ ), the power is lower and the fluctuations are decoupled from those detected at lower latitudes. Previous studies have shown that the fluctuation power level is maximum at the latitude of the cusp (Matthews et al., 1996; Yagova et al., 2002) and that the correlation between fluctuations at auroral and polar cap lati-

tudes is really poor (Yagova et al., 2002); in this sense, our results seem to indicate that ZYK could be close to the auroral oval, whose position depends on geomagnetic activity, expanding to lower latitudes as activity increases (Kamide, 1988), and that CHD could be located at the footprint of open field lines. It is remarkable that in the same hours, the SW pressure shows several variations that find a correspondence in the  $H$  component variations only at CHD; this finding seems to suggest that, in the recovery phase of a major storm, the response of the geomagnetic field to SW pressure variations is generally masked by the effects of magnetospheric storm-substorm current systems, so it can be detected only at the footprint of the outermost field lines, which are close to the magnetopause.

Some hours later, i.e. just after the local noon along the European array and in the premidnight sector along the 210 MM array, there is another time interval during which the SW pressure shows large variations; in this case, they find a close correspondence with the  $H$  component variations at all stations, indicating a global response to the external continuous stimulations. Along the 210 MM array, the ground response does not show a clear latitudinal dependence. Conversely, along the European array, the amplitude of the response grows monotonically with the geomagnetic latitude from  $\sim 21$  nT/(nPa) $^{1/2}$  to  $\sim 53$  nT/(nPa) $^{1/2}$ ; this result could be explained by taking into account that at higher latitudes, the geomagnetic field lines are closer to the current systems, both in the high-latitude ionosphere and on the magnetopause, which vary with varying SW pressure and are responsible for the variation of the ground  $H$  component in the dayside sector (Russell and Ginskey, 1995; Francia et al., 1999). The latitudinal increase of the response becomes more steep at a latitude of  $\sim 55^\circ$ , roughly corresponding to the position of the plasmopause during disturbed magnetospheric conditions (Chappell et al., 1970).

We note that the response at AQU is slightly higher than the one found at the same local time and station in a previous statistical analysis (Francia et al., 1999); also, at subauroral latitudes, the response, both just after local noon (at NUR) and before midnight (at MGD), is considerably higher than that found statistically at the same latitudes by Russell and Ginskey (1995); these results could be understood by taking into account that the event analyzed in this study occurs during summer, when the ionospheric conductivity is maximum.

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## References

- Baransky, L. N., Borovkov, J. E., Gokhberg, M. B., Krylov, S. M., and Troitskaya, V. A.: High resolution method of direct measurement of the magnetic field lines eigenfrequencies, *Planet. Space Sci.*, 33, 1369–1374, 1985.
- Chappell, C. R., Harris, K. K., and Sharp, G. W.: The reaction of the plasmapause to varying magnetic activity, particle and fields in the magnetosphere, McCormac, B. M. (Ed.), Dordrecht, D. Reidel, 148, 1970.
- Chen, L. and Hasegawa, A.: A theory of long period metric pulsations, 1, steady state excitation of field line resonance, *J. Geophys. Res.*, 79, 1024–1037, 1974.
- Chisham, G. and Orr, D.: A statistical study of the local time asymmetry of Pc 5 ULF wave characteristics observed at midlatitudes by SAMNET, *J. Geophys. Res.*, 102, 24 339–24 350, 1997.
- Francia, P. and Villante, U.: Some evidence of ground power enhancements at frequencies of global magnetospheric modes at low latitude, *Ann. Geophysicae*, 15, 17–23, 1997.
- Francia, P., Lepidi, S., Villante, U., Di Giuseppe, P., and Lazarus, A. J.: Geomagnetic response at low latitude to continuous solar wind pressure variations during northward interplanetary magnetic field, *J. Geophys. Res.*, 104, 19 923–19 930, 1999.
- Harrold, B. G. and Samson, J. C.: Standing ULF modes of the magnetosphere: a theory, *Geophys. Res. Lett.*, 19, 1811–1814, 1992.
- Gonzalez, W. D., Tsurutani, B. T., and Clua de Gonzalez, A. L.: Interplanetary origin of geomagnetic storms, *Space Science Rev.*, 88, 529–562, 1999.
- Kamide, Y.: Electrodynamics processes in the Earth's ionosphere and magnetosphere, Kyoto Sangyo Univ. Press, 1988.
- Kamide, Y., Baumjohann, W., Daglis, I. A., et al.: Current understanding of magnetic storms: storm-substorm relationship, *J. Geophys. Res.*, 103, 17 705–17 728, 1998.
- Kivelson, M. and Southwood, D.: Resonant ULF waves: a new interpretation, *Geophys. Res. Lett.*, 12, 49–52, 1985.
- Kivelson, M. and Southwood, D.: Coupling of global magnetospheric MHD eigenmodes to field line resonances, *J. Geophys. Res.*, 91, 4345–4351, 1986.
- Lepidi, S., Francia, P., Villante, U., Meloni, A., Lazarus, A. J., and Lepping, R. P.: The Earth's passage of the April 11, 1997 coronal ejecta: geomagnetic field fluctuations at high and low latitude during northward interplanetary magnetic field conditions, *Ann. Geophysicae*, 17, 1245–1250, 1999.
- Mann, I. R., Wright, A. N., Mills, K. J., and Nakariov, V. M.: Excitation of magnetospheric waveguide modes by magnetosheath flows, *J. Geophys. Res.*, 104, 333–353, 1999.
- Matthews, D. L., Ruohoniemi, J. M., Dudeney, J. R., Farrugia, C. F., Lanzerotti, L. J., and Friis-Christensen, E.: Conjugate cusp-region ULF pulsation responses to the solar wind event of May 23, 1989, *J. Geophys. Res.*, 101, 7829–7841, 1996.
- Mathie, R. A., Mann, I. R., Menk, F. W., and Orr, D.: Pc5 ULF pulsations associated with waveguide modes observed with the IMAGE magnetometer array, *J. Geophys. Res.*, 104, 7025–7036, 1999.
- Mathie, R. A. and Mann, I. R.: Observations of Pc5 field line resonance azimuthal phase speeds: a diagnosis of their excitation mechanism, *J. Geophys. Res.*, 105, 10 713–10 728, 2000.
- Menk, F. W., Orr, D., Clilverd, M. A., Smith, A. J., Waters, C. L., Milling, D. K., and Fraser, B. J.: Monitoring spatial and temporal variations in the dayside plasmasphere using geomagnetic field line resonances, *J. Geophys. Res.*, 104, 19 955–19 969, 1999.
- Menk, F. W., Waters, C. L., and Fraser, B. J.: Field line resonances and waveguide modes at low latitudes. 1. Observations, *J. Geophys. Res.*, 105, 7747–7761, 2000.
- Ogilvie, K. W. and Burlaga, L. F.: A discussion of interplanetary postshock flows with two examples, *J. Geophys. Res.*, 79, 2324–2330, 1974.
- Radoski, H. R.: A theory of latitude dependent geomagnetic micropulsations: the asymptotic fields, *J. Geophys. Res.*, 79, 595–603, 1974.
- Rostoker, G. and Sullivan, B. T.: Polarization characteristics of Pc5 magnetic pulsations in the dusk hemisphere, *Planet. Space Sci.*, 35, 429–438, 1987.
- Russell, C. T. and Ginskey, M.: Sudden impulses at subauroral latitudes: response for northward interplanetary magnetic field, *J. Geophys. Res.*, 100, 23 695–23 702, 1995.
- Russell, C. T., Ginskey, M., and Petrinec, S. M.: Sudden impulses at low latitude stations: steady state response for northward interplanetary magnetic field, *J. Geophys. Res.*, 99, 253–261, 1994.
- Samson, J. C., Greenwald, R. A., Ruohoniemi, J. M., Hughes, T. J., and Wallis, D. D.: Magnetometer and radar observations of MHD cavity modes in the Earth's magnetosphere, *Can. J. Phys.*, 69, 929–937, 1991.
- Samson, J. C., Harrold, B. G., Ruohoniemi, J. M., Greenwald, R. A., and Walker, A. D. M.: Field line resonances associated with MHD waveguides in the magnetosphere, *Geophys. Res. Lett.*, 19, 441–444, 1992.
- Shimazu, H., Araki, T., Kamei, T., and Hanado, H.: A symmetric appearance of Pc5 on dawn and dusk side associated with solar wind dynamic pressure enhancement, *J. Geomag. Geoelect.*, 47, 177–189, 1995.
- Sibeck, D. G., Baumjohann, W., Elphic, R. C., Fairfield, D. H., Fennell, J. F., Gail, W. B., Lanzerotti, L. J., Lopez, R. E., Luehr, H., Lui, A. T. Y., MacLennan, C. G., McEntire, R. W., Potemra, T. A., Rosenberg, T. J., and Takahashi, K.: The magnetospheric response to 8-minute period strong amplitude upstream pressure variations, *J. Geophys. Res.*, 94, 2505–2519, 1989.
- Southwood, D. J.: Some features of field line resonances in the magnetosphere, *Planet. Space Sci.*, 22, 482–491, 1974.
- Takahashi, K.: ULF waves: 1997 IAGA division 3 reporter review, *Ann. Geophysicae*, 16, 787–803, 1998.
- Villante, U., Francia, P., Lepidi, S., De Lauretis, M., Pietropaolo, E., Cafarella, L., Meloni, A., Lazarus, A. J., Lepping, R. P., and Mariani, F.: Geomagnetic field variations at low and high latitude during the January 10–11, 1997 magnetic cloud, *Geophys. Res. Lett.*, 25, 2593–2596, 1998.
- Villante, U., Francia, P., and Lepidi, S.: Pc5 geomagnetic field fluctuations at discrete frequencies at a low latitude station, *Ann. Geophysicae*, 19, 321–325, 2001.
- Walker, A. D. M., Ruohoniemi, J. M., Baker, K. B., Greenwald, R. A., and Samson, J. C.: Spatial and temporal behavior of ULF pulsations observed by Goose Bay HF radar, *J. Geophys. Res.*, 97, 12 187–12 202, 1992.
- Waters, C. L., Menk, F. W., and Fraser, B. J.: The resonance structure of low latitude Pc3 geomagnetic pulsations, *Geophys. Res. Lett.*, 18, 2293–2296, 1991.
- Waters, C. L., Samson, J. C., and Donovan, E. F.: The temporal variation of the frequency of high latitude field line resonances, *J. Geophys. Res.*, 100, 7987–7996, 1995.
- Yagova, N., Lanzerotti, L., Villante, U., Pilipenko, V., Lepidi, S., Francia, P., Papitashvili, V., and Rodger, A.: ULF Pc5–6 magnetic activity in the polar cap as observed along a geomagnetic meridian in Antarctica, *J. Geophys. Res.*, in press, 2002.

- Ziesolleck, C. W. S. and Chamalaun, F. H.: A two-dimensional array study of low-latitude Pc5 geomagnetic pulsations, *J. Geophys. Res.*, 98, 13 703–13 713, 1993.
- Ziesolleck, C. W. S. and McDiarmid, D. R.: Auroral latitude Pc5 field line resonances: quantized frequencies, spatial characteristics and diurnal variations, *J. Geophys. Res.*, 99, 5817–5830, 1994.
- Ziesolleck, C. W. S. and McDiarmid, D. R.: Statistical survey of auroral latitude Pc5 spectral and polarization characteristics, *J. Geophys. Res.*, 100, 19 299–19 312, 1995.